ESL-HH-02-05-27

DEVELOPMENT AND ANALYSIS OF A SUSTAINABLE LOW ENERGY HOUSE IN A HOT AND HUMID CLIMATE

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ABSTRACT

This study examines the lifetime building energy consumption of a typical house in Bangkok, Thailand. The lifetime building energy consumption is composed of three major components: 1) the energy used in building construction (i.e., embodied, transportation and construction energy), 2) the energy used in building operation (annual energy), and 3) the energy used in building demolition (demolition energy).

The study used measured environmental and energy use data from a case-study house in Thailand. For the construction energy and the energy used in building demolition analyses, reference data from reliable sources both in the U.S. and the U.K. were used. The DOE-2 energy simulation program was used to analyze changes to the annual energy use caused by changing various building materials and/or design configurations. A new energy efficient design was then iteratively chosen that contained reduced levels of embodied energy use and reduced annual energy use.

The results from the analysis showed that the total lifetime energy use was reduced from 3,974 to 2,773 MMBtu (a 30% reduction). This was accomplished by replacing energy intensive materials with less energy intensive materials that were also energy efficient, namely the masonry walls. The addition of insulation in the ceiling and energy efficient windows was also included.

INTRODUCTION

The efficient use of energy has increasingly become more important as the world's population grows and new supplies of energy become more expensive to develop. This issue also affects the global economy due to the increasingly high cost of energy. Thailand, a developing country, imports a large amount of its energy. As a result, energy efficiency is one of the key elements to improve Thailand's economic and living standard. Unfortunately, many of the methods for conserving energy have been developed by industrialized countries for use in those countries and may not be appropriated for another country because of differences in population and growth rates, energy sources, income levels and life styles. To illustrate this point, one can compare the U.S. population, energy use, and income with Thailand's population, energy use, and income.

According to the United Nations (1999), in 1995 the world population was 5,667 million, with an annual growth rate of 1.46%. In the United States, the population was 267 million (4.71% of the world's population), with an annual growth rate of 0.99%, whereas Thailand's population was 59 million (1.04% of the world's population), with an annual growth rate of 1.06%. Clearly, one can see that the world's population growth rate is 50% higher than the United States' population growth rate, while Thailand's population growth rate stands closer to the growth rate of the United States.

The United Nations' report also showed that the world population density was 42 people/km^2. In the United States, the population density was 29 people/km^2, whereas Thailand's population density was 114 people/km^2. Therefore, even though Thailand's population is approximately 5 times (4.53) less than the United States' population, Thai people live in high-density urban areas, almost 4 times (3.93x) more crowded than Americans experience.

In regards to energy use, according to the Energy Information Administration (EIA, 1998), in 1995 the world's total annual energy use was 363 quadrillion Btu (1 quad = 1 x 10^{15} Btu). In the United States, the total energy use was 82 quads (22.5% of the world's energy use), whereas Thailand's total energy use was only 3 quads (0.83% of the world's energy use). The EIA's report also showed that the world energy use per capita was 65.5 MBtu/person (2.19 kW). In the United States, the energy use per capita was 313.47 MBtu/person (10.48 kW), whereas Thailand's energy use per capita was 49.6 MBtu/person (1.66 kW). From this comparison, one can see that Thailand consumed approximately 6 times less energy use per capita than the United States did and approximately 3/4 of the world's energy use per capita. Therefore, it seems that Thailand is already an efficient energy consumer, and has little to learn from the United States. However, one cannot see the complete picture without considering Thailand's economic activities and how these economic activities compare with other countries.

Regarding the economic activities, according to the EIA (1998), in 1995 the world Gross Domestic Product (GDP) was $23.35 trillion (US$), averaging $4,212 per capita. In the United States, the GDP was $6.14 trillion (26.33% of the world's GDP), averaging $23,380 per capita, whereas Thailand's GDP was $0.12 trillion US$ (0.55% of the world's GDP), averaging $2,206 per capita. Clearly, although Thailand's economic activity was 1/2 of the world's GDP, it was only 1/10 of the United States' GDP. Clearly, this is another contributing factor to Thailand's low energy use, and it restricts Thailand in its ability to invest in energy efficiency measures that carry a big price tag.

Finally, the last option to consider is that Thailand wants to become more like the United States and other developed countries. Unfortunately, there are some inefficient bad habits of energy consumption that Thailand should not adopt from the United States. Thailand cannot afford to make the same mistakes that the developed countries have made because of their limited per capita income. Therefore, the most effective way for Thailand to move ahead with its economic expansion is with energy efficient technologies and consumer products. This especially applies to Thailand's future residential sector, which consumes 30 % of the total nation's energy use (Thongpiyapoom, 1994).

LITERATURE REVIEW

Sustainability. The term "sustainable" is widely used by architects today. However, it is hard to find an exact definition without being influenced by the authors' value judgment and subjectivity (Steele, 1997). The term "sustainable" deals with almost everything around us, for example, energy and water use, waste and recycling, air pollution, land use, and degradation of plant and animal habitats. To illustrate this point, the following definitions are reviewed (Steele 1997; Ness 1998). According to Steele, "Sustainability is evocative of optimistic and protective ideas, recalling sustenance and, therefore, a nurturing, or at least good common sense. Linked as it has been to development, which implies its own set of desirable goals and growth, sustainability's connotations are those of building a solid future and achieving prolonged, lasting, worthwhile progress" (Steel, 1997, p. ix). Unfortunately, it is hard to convert such a statement into design advice.

A more useful definition for building designers is given by Ness, at the Green Building Conference, who defines sustainability as: "products, systems, buildings, and land planning that create and promote an environment for healthy human living which can be sustained into the future-unpolluted by its waste or by products; thus, preserving and maintaining our natural resources for future generations" (Ness, 1998, p.25). A statement that is a little closer to something resembling design advice.

There are many organizations concerned with the embodied energy use of construction materials. These organizations have tried to evaluate the impact of construction materials on the environment as well as the quality and energy performance of construction materials. For example, the U.K. Eco-Labeling Board, set up in 1992, has been developing criteria for product groups and is trying to emphasize the use of products that have smaller impact on the environment during their life cycle (Edwards, 1996).

In the U.S., Crowther (1992) suggested that the selection of construction materials for energy efficient sustainable design should be ecologically appropriate, nontoxic and non-allergenic. He also suggested that they should come from a local resource, be renewable and sustainable, recyclable, multifunctional, natural, and should only require a short distance of transport. Finally, he said that they should be durable and long lasting, and have a useful life expectancy, and they should also be functional with minimum utility energy use, and be easy to maintain and repair, with components that can be reused in the future – virtually a template for good design advise.

Thermal comfort. Unfortunately, thermal comfort often takes the back seat when sustainability only is driving the design. For many building owners this is not acceptable. In order to achieve effective design in hot humid climates, one needs to understand thermal comfort, how the human body interacts with its surroundings, adaptation in hot humid climate, and the prediction of thermal comfort (i.e., the ASHRAE Comfort Chart). There are several different definitions of thermal comfort. According to the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), thermal comfort is defined as "…that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 1997, p.8.1), which for the most part, is defined by the ASHRAE Comfort Chart. Unfortunately, the ASHRAE Comfort Chart is really for heated or air conditioned buildings and may not be the most useful chart for natural ventilated buildings. Another definition of thermal comfort was developed by Givoni (1998) who stated that thermal comfort could be defined as the range of climatic conditions considered comfortable and acceptable to humans. Therefore, in this study, the thermal comfort of the case study house will be evaluated to understand the living conditions in Bangkok, Thailand.

Previous Design Strategies. There are many strategies and methods for designing low energy houses in hot and humid climate. The following are some of the recommended design strategies and case studies: A) *Building Orientation.* Air motion is one of the primary requirements for physiological comfort in humid regions (Givoni, 1976). B) *Solar Orientation and window shading*. From the research by the Thai Gypsum Products Public Company (TG, 1995), the main objective in building orientation in Thailand is to minimize the impact of solar heating. C) *Wind Orientation*. Givoni's studies (1976) and TG's studies (1995) reached similar conclusions for hot and humid climates, namely buildings should be oriented perpendicular to the direction of the prevailing wind and should contain large openings to allow the wind to flow throughout the building. D) *Landscape Orientation.* The orientation of a building relative to vegetation and landscape features can also be affected by natural ventilation (TG, 1995; Boonyatikarn, 1997). E) *Daylighting*. Lighting the interior of a building with natural light is not only energy efficient, but also improves the aesthetics of the interior. However, for thermal and glare reasons, direct sunlight should be excluded from striking the building interior (Boonyatikarn, 1997). In summary, building orientation, solar orientation, wind orientation, position relative to the landscape, daylighting and other methods (i.e., ventilation, thermal mass, color, low energy appliances, ground water cooling) have been shown to have a substantial impact on a building's thermal comfort, especially for unconditioned buildings.

Organizations and Tools that evaluate Sustainable Architecture. There are many nonprofit organizations performing research in both the residential and commercial sustainability. Examples of large and well-known organizations are the " U.S. Green Building Council", and the "Building Research Establishment" (BRE 2002) in the U.K. The U.S. Green Building Council (USGBC 2002), founded in 1993, is a non-profit organization that provides knowledge and action on environmental issues for commercial and industrial buildings. The headquarters are located in San Francisco, California. The council has grown to more than 500 leading international organizations. Its goal is to help the building industry develop products that are more environmentally and economically viable and to drive the marketplace forward towards the development of high performance buildings (U.S. Green Building Council 2002).

"The Leadership in Energy and Environmental Design (LEED) Green Building Rating System" is the voluntary, consensus-based, market-driven building rating system of the U.S. Green Building Council that is used to evaluate environmental performance from a whole-building perspective over a building's life cycle and to provide a definitive standard for a "green building". Different levels of green building certification are awarded based on the total credits earned.

The Building Research Establishment (BRE) is the U.K.'s leading center for construction and fire expertise providing research, complementary activities, education, built environment consultancy and information services to customers worldwide. BRE shares this mission with its owner, "the Foundation for the Built Environment" formed in 1961. BRE was transferred to the private sector in 1997. The main head office is in Watford, England. The Foundation for the Built Environment's income comes from the surplus generated by trading activities (including BRE), donations, investments, etc. BRE has launched the Environmental Impact Estimating Design Software (ENVEST), the first U.K. software for assessing life cycle environmental impacts of buildings from the early design stage (Center for Sustainable Construction, 2000).

METHODOLOGY

General. A building's lifetime energy consumption is composed of 3 major parts: 1) the energy used in building construction (embodied energy), 2) the energy used in building operation (annual energy), and 3) the energy used in building demolition. In this study, all 3 parts were examined, with the primary focus on the energy used in building construction and building operation.

As shown in Figure 1, the first part of a building's lifetime energy consumption is the energy used in building construction (embodied energy). It contains 4 subcomponents: 1) the energy used for manufacture of materials and components, 2) the energy used for direct fuel purchases for construction processes, 3) the energy used for administration and professional service, and 4) the energy used for transport of materials and equipment. In the case study site, the energy used for all four subcomponents was calculated and combine with the second component, the energy used in building operation.

The second part, the energy used in building operation (annual energy) is shown. It contains 3 subcomponents: 1) electricity, 2) natural gas, and 3) water. In hot and humid regions such as Thailand, electricity is used for lighting, equipment, and space cooling. In cold-climate countries, electricity is often used for space heating as well. Natural gas is mainly

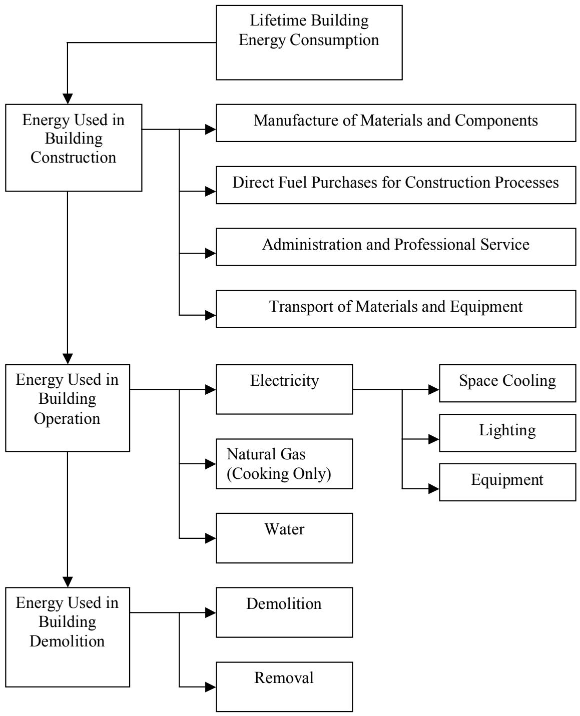

Figure 1: *Lifetime Building Energy Consumption Components for a Typical Residence in Thailand.*

used for only cooking for hot and humid climates such as Thailand. In cold climates, gas is also used for space heating. Water is used for cooking and cleaning. In most instances, significant amounts of energy are needed to provide water from the natural sources to a building. However, in this study, only the energy used for heating the water was considered.

The final part of the lifetime building energy consumption is the energy used in building demolition. It contains 2 subcomponents: 1) energy used in building demolition and 2) the energy used for material removal. Finally, the energy use of the three main parts was combined to obtain the total lifetime building energy consumption.

Therefore, the methodology employed in this study (Chulsukon 2002) is composed of 2 primary tasks that were applied in an iterative fashion, namely: 1) calculating the embodied energy of the base-case house and of the new energy efficient house, and 2) evaluating the annual energy use of the base-case house and of the proposed construction using the DOE-2 energy simulation program. These processes are shown in Figure 2.

Embodied Energy Data. The embodied energy of the case study house and the newly designed house was calculated using data from the several sources: 1) The Handbook of Building Construction (1980), issued by the U.S. Department of Energy, and based on the research by The Stein Partnership and The Center for Advanced Computation, now called the Energy Research Group of the University of Illinois.

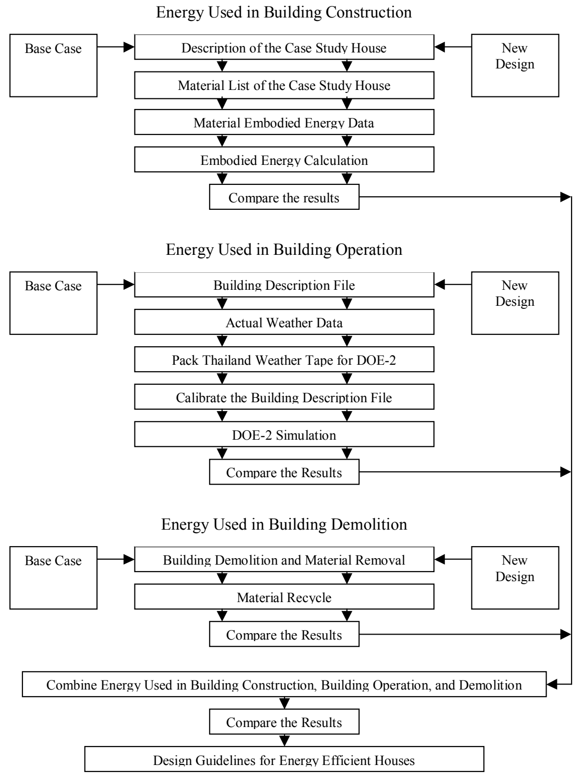

Figure 2: *Methodology.*

2) Embodied energy use published by Cambell (1992) who conducted research in Franklin, Texas, a "General Law" city method for classifying small cities, as a case study model. The model assesses current physical condition and use of resources and compares findings against a performance standard. 3) The Environmental Resource Guide (1992), which is a publication of embodied energy and materials by The American Institute of Architects (AIA). 4) The textbook by Stein and Reynolds (1992). Stein was also the head of the research team that conducted research on embodied energy in buildings for the U.S. Department of Energy in the 1970's. 5) The Environmental Resource Guide (1996), which is the updated version from the 1992 Environmental Resource Guide by the American Institute of Architects (AIA).

Energy in Building Operation. In this study, the energy used in building operation is analyzed using the DOE-2.1e program, which includes the following subtasks: A) Build the building description file, B) Gather actual weather data from Thailand, C) Pack Thailand weather tape for DOE-2.1e, D) Calibrate the building description file to the base-case building, E) Make specific changes to the base-case file representing the new proposed construction, F) Evaluate the energy savings.

Building Description File For the DOE-2 energy simulation program, the following data were used to provide the DOE-2 input file: A) Building location = Bangkok actual data, B) Construction materials = Data referenced from DOE2.1e library from the DOE2.1e manual (US. Department of Energy, 1994), and data from the Mechanical and Electrical Equipment for Buildings (Stein and Reynolds, 1992), C) Occupancy Schedule = Interviews with the case study occupants, D) Lighting Schedule = Interviews with the case study occupants, and collection and measurement of the actual data from the site, E)Equipment Schedule = Interviews with the case study occupants, and collection and measurement of the actual data from the site. F) A/C schedules = Interviews with the occupants, and collection and measurement of actual data from the site. G) Space Details = Simulation of the house from the drawings, and use of measured data using portable data loggers or average data for each specific space.

Weather Data. Weather data from the Royal Thai Meteorological Department were used to create the specific weather file for Bangkok, Thailand. In order to create a new weather file for Bangkok during the year 2000 period, the following components were needed: A) City latitude, longitude, standard time meridian, and elevation above sea level, B) Hourly dry-bulb temperatures for 12 months, C) Hourly relative humidity (RH) for 12 months, D) Hourly solar radiation on horizontal surface for 12 months, and E) Hourly wind speed for 12 months. All raw data were fed into the DOE-2 weather packer software (provided with the DOE2.1e program) to create the new weather file for the DOE-2 energy simulation program.

Figure 3: *Portable Temperature/humidity Data logger.*

Instrumentation. The Onset Computer Corporation's HOBO-H8 RH/TEMP Loggers were used to collect temperature and relative humidity of the case study house. Five 2-Channel HOBO data loggers and one 4-Channel portable data logger were installed in different zones (Figure 3).

DOE-2 Simulation Calibration. For this study, three primary comparisons were used for the calibration: 1)Average monthly electricity use was used as a comparison between the actual monthly electricity use from the electricity bills and the monthly electricity use from the DOE-2 simulation. 2) Average daily electricity use was used as a comparison between the actual daily electricity use (i.e., selected weeks of manual daily readings) and the daily electricity use from the DOE-2 simulation. 3) Simulated zone temperatures were compared with the actual temperatures from three selected zones: a) main dining room, b) master bedroom, and c) attic.

Energy Conserving Strategies Investigation. After the DOE-2 simulation of the base-case house was calibrated, the base-case simulation was then modified to include new features. The following investigations were then studied: brick walls (with and without insulation), light weight walls, cement tile roofs (with and without insulation), glazing (single-clear, double-clear, double-reflective coating), and light versus dark external coloring for colored roofs and walls.

RESULTS

Case Study House Characteristics.

The case study house, located in Bangkok, Thailand, was chosen because it represents a typical middle class house in Bangkok, Thailand. From the research by Thongpiyapoom (1994), a middle class Thai house has the following general characteristics: A) Two-story, B) Pitched roof with concrete tile covering, C) Three-bedroom and three-bathroom, D) Four-inch brick wall with white-painted plaster finish of the exterior, E) Concrete slab floor, F) Single pane glass with wood frame casement windows.

The house has slab-on-beam reinforced concrete construction, with prefabricated concrete panels. The house has a pitched roof with a wooden support for the cement tiles (NOTE: steel roof structures are becoming more popular due to the lack of the wood for the structural support). Windows are single-pane tinted glass. Table 1 summarizes the case study house description. Figures 4 and 5 are photos of the right and front elevations. Figure 6 is a photo of the cement tile roof. Figure 7 provides a illustration of the DOE-2 input file used for the base-case simulation.

Figure 4. *Right Elevation (East). The east side is adjacent to the neighbor's house. However, there is some green space between these two houses and no shade from the neighbor's house.*

Figure 5. *Front Elevation (South). The front side is adjacent to the street. There is no shade from other buildings.*

As seen from the photos, the case study house has 2 buildings, the main building and the service building. The main building has a dining room, a living room, a bathroom, and a drawing room on the first floor. It has 3 bedrooms and 2 bathrooms on the second floor. The service building has a kitchen, a maid bedroom, a maid bathroom, and storage. The first floor has an area of 120.75 m^2 (1,300 ft^2), the second floor has total enclosed area of 87.75 m^2 (944 ft^2), and the service building has an area of 85 m^2 (914 ft^2) for a total floor area of 293.5 m^2 (3,159 ft^2).

Since a typical house in Thailand relies on natural ventilation, there are a many operable windows in this house. However, all bedrooms in the house, including a living room and a drawing room, have mini-split air conditioning units, which are used in the evenings when the bedrooms are occupied. Since the wind blows from the south to the north in Thailand during most of the cooling season, the front of the house faces the south with few obstructions to allow for maximum ventilation. The service building is located to the north of the main building to prevent smoke from the kitchen from being brought into the main building by the wind. The carport was located on the west to shade the main building from the afternoon sunlight. The second floor is cantilevered 1.5 meters over the first floor to help shade the building.

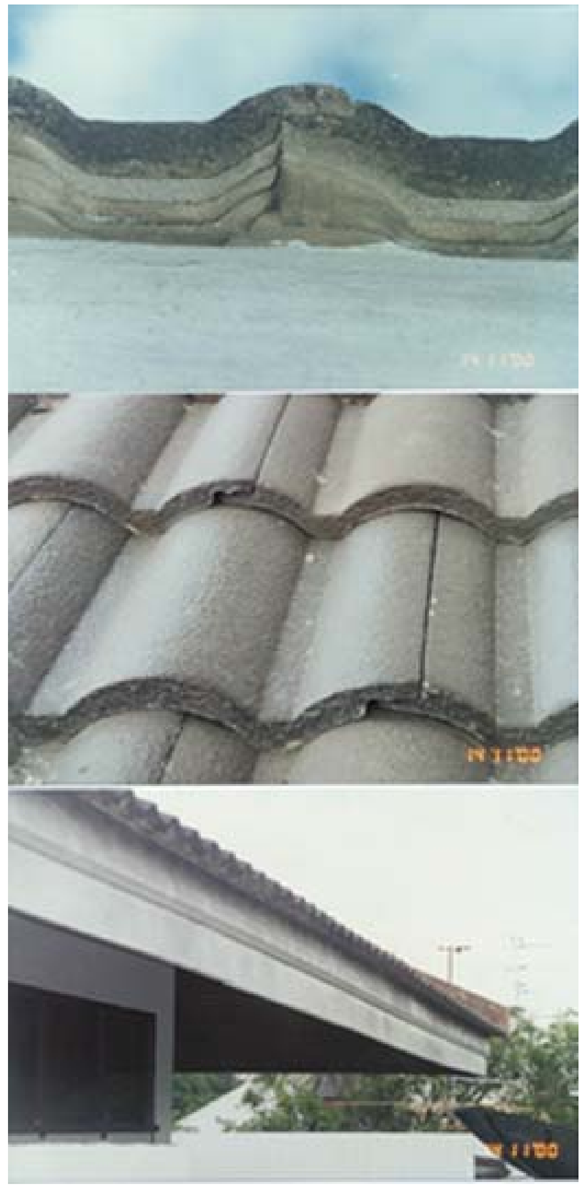

Figure 6. *Case Study House's Cement-Tile Roof. The cement-tile panels are overlapped on each other. The gaps allow air ventilation to cool the attic space.*

<u>On-site temperature and humidity measurements</u>. Six portable data loggers (7 channels) were installed to collect dry bulb temperature and relative humidity. The data logger's time period was set at 30-minute intervals. The data loggers were located in the following locations: 1) Exterior – The data logger was placed in a small basket, hung outside the house

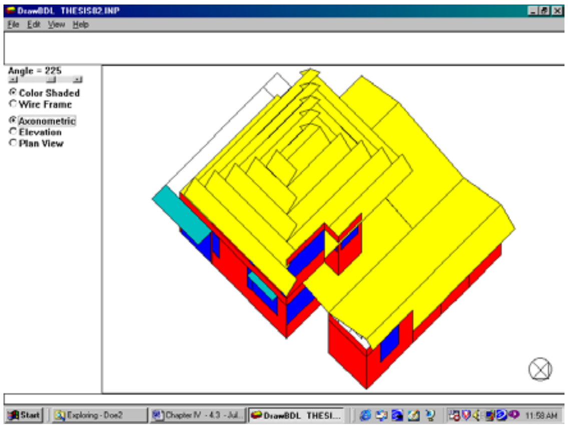

Figure 7. *The Case Study House from Draw BDL Program.*

Building Type	Residential Building / 2-story House
Location	Bangkok, Thailand
Built	1984
Area	3,159 ft^2 (293.5 m^2)
Construction	Post and Beam / Reinforce Concrete
Materials	
Floor	Slab on Beam Reinforce Concrete
	Parquet / Ceramic Tile / Marble / Carpet
Wall	Brick Wall
Roof	Wood Structure
	Cement Tile Roof
Window and Door	Wood Frame / Aluminum Frame
	Wood Door / Glass Door and Glass Window

Table 1: *Case Study House Description.*

at the north in the shade to measure exterior air temperature. 2)Dining room / unconditioned zone – The data logger was placed on the shelf in the dining room and recorded temperature and relative humidity. 3) Interior ground temperature – This was recorded using a remote probe attached to the data logger in the dining room that was taped to the floor with metal-backed tape and covered with 2” of insulation. 4) Master bedroom / conditioned zone – The data logger was placed in the room and shielded from direct sunlight. 5) Second floor hall / unconditioned zone – The data logger was placed on the top of the closet board. 6) Lower attic / unconditioned zone – The data logger was placed on the top of the ceiling of the second floor hall that is the floor of the attic. 7) Upper attic / unconditioned zone - The data logger was hung on the top of a long wooden stick. The wooden stick was then used to reach the top of the attic.

DOE-2 Input File. The DOE-2 input file was assembled from the as-built drawings and calibrated to the interior temperatures (Tables 2 and 3). From January to July 2000, an 82 F average monthly ground temperature was used (Boonyatikarn, 1997), measured average monthly ground temperatures were used for the remaining period (apx. 82.8 F). In the case study house single-pane tinted glass was used for the base case. LOADS schedules were developed from on-site measurements and occupant interviews for the occupancy, lighting and equipment schedules (Figure 8).

Space Condition	Residence		Note
Temperature	80	F	Estimate from HOBO - Uncond. Zone
Number of People	4	Persons	Actual Data
Lighting Type	Fluoresent		Actual Data
Light to Space	0.8	80%	Reference from Habitat House Case Study
Infiltration Method	Air Change / hr		Reference from Habitat House Case Study
Air Change / hr	1		Reference from Habitat House Case Study
Floor Weight	0		Reference from Habitat House Case Study
Zone Type	Uncond. & Cond.		Actual Data
Space Condition	**Attic**		**Note**
Temperature	88.5	F	Estimate from HOBO - Attic
Number of People	0	Persons	Actual Data
Lighting Type	Fluoresent		Actual Data
Light to Space	0.8	80%	Reference from Habitat House Case Study
Infiltration Method	Air Change / hr		Reference from Habitat House Case Study
Air Change / hr	60		Estimate from DOE-2 Analysis
Floor Weight	0		Reference from Habitat House Case Study
Zone Type	Uncond.		Actual Data

Table 2. *SPACE-CONDITIONS Details. Input values shown above were referenced from the Habitat House case study (Kootin-Sanwu 2000).*

Zone Control			Note
Design-Heat-T	55	F	No Heating
Design-Cool-T	77	F	Actual Data
Thermostat	Two-Position		On/Off

Table 3. *Zone Control Details.*

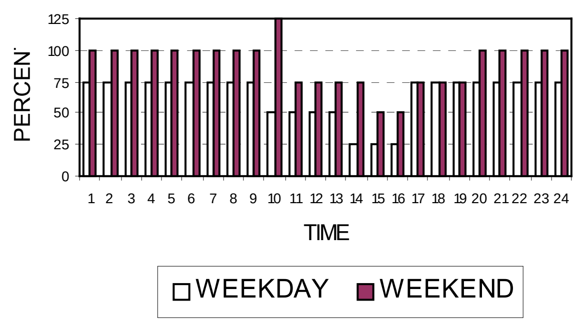

Figure 8. *Typical Occupancy Profile. This schedule was used to represent the occupancy for the 4 people that lived in the house. Visits by guests were counted as 100%+ occupancy.*

In the spaces an air change rate equal to 1 was used to represent the measured conditions. For the attic, a ventilation rate equal to 60 Air Change/Hour was found to best match the average measured air temperature (i.e., the average of the lower and upper air temperatures). Specific details were varied for each space to match the observed occupancy profiles. All walls, floors, and ceilings are defined in the

DOE-2 X, Y, and Z coordinates from the 0,0,0 building reference point to account for shading. Figure 7 is a graphical representation of the house using the DrawBDL program (Huang 2000). Wall descriptions were developed to closely match the actual materials.

Table 4 shows the details used in the Zone Control Command. Since there are five mini-split air conditioners in the house that are manually controlled, individual schedules were developed for each zone that represented the observed on/off schedule. Air conditioning efficiencies were matched to manufacturer's data.

Cooling Capacity	Area (ft2)	Area (m2)	Cooling Capacity (Btu)	Note
SYS1-2 / Living	344.45	32	26,690	Actual Data
SYS1-3 / Drawing	438.63	41	26,690	Actual Data
SYS2-1 / MBR	344.45	32	28,118	Actual Data
STS2-2 / BR 1	177.22	16	12,992	Actual Data
SYS2-3 / BR2	177.22	16	12,992	Actual Data

Table 4. *System Control Details.*

Calibration of the DOE-2 Simulation. Thailand is located in Southeast Asia, at a Longitude of 98 degrees East to 106 degrees East, and from Latitude 6 degrees South to 20 degrees North, a hot and humid climate. Bangkok is the capital city of Thailand located in the central part of the country. The study period was the year 2000. Weather data gathered from the Royal Thai Meteorological Department are shown in Figures 9 and 10. In Figure 9 the average monthly temperatures are very constant at about 80 to 85 F. Temperatures increase slightly from March to May, which is a summer season for Thailand. For these months, the hot and humid southeast wind blows through the country from the Pacific ocean, bringing numerous rainstorms. From November to February, the minimum temperatures decrease slightly, which represent the winter season for Thailand when a cold northeast wind from China blows through the country.

In Figure 10, the average monthly relative humidity is shown to be above 60%, which is the maximum for human comfort (ASHRAE, 1997). At high relative humidity, mold forms and causes problems for Thai residences. As a result, humidity control is a very important concern. As previously stated, in the summer season, hot and humid air is drawn across Thailand from the Pacific Ocean. Therefore, the period from April to August has higher relative humidity than other months. During the period from November to February, when the cold, dry wind blows through Thailand from the northwest, relative humidity is considerably lower.

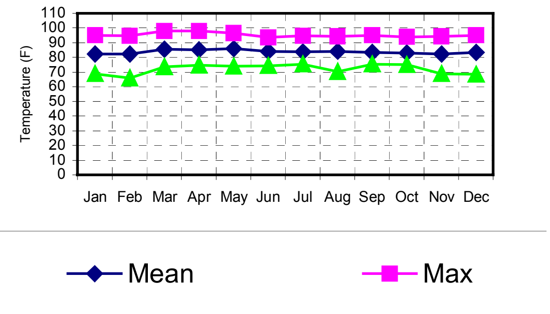

Figure 9. *Bangkok 2000 Drybulb Temperature. Thailand has a hot and humid climate. The average temperatures change very little each month. The monthly average temperatures are above 80 F (26.6 C) year round (source: the Royal Thai Meteorological Department, 2000).*

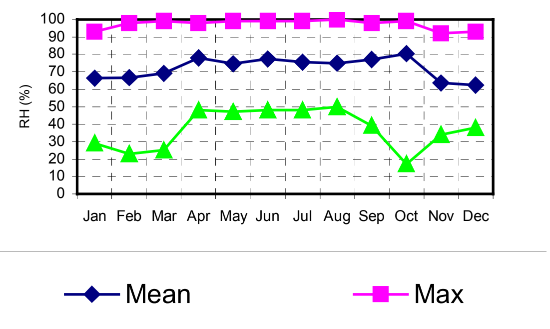

Figure 10. *Bangkok 2000 Relative Humidity. Thailand has hot and humid climate. The relative humidity is very high all the year round. Therefore, the humidity control is concerned as one of important factors for comfort condition in building design (source: the Royal Thai Meteor. Department, 2000).*

One year of hourly data for 2000 were used to create a Thailand weather file for the DOE-2. A two week period was then used to ascertain if DOE-2's predicted interior temperatures were matching the measured zone temperatures (Figure 11). Monthly simulated data were compared to six months of actual utility bills for the period from July to December 2000 (Figure 12). Daily simulated data were also compared to a two week period in December (Figure 13).

Energy Embodiment The total embodied energy of the case study house is shown in Table 5. The second and third columns show the quantities of each material and the units. The forth and fifth columns show the quantities of materials in IP units because the IP units are most often reported in the U.S. literature. The sixth column shows the embodied energy per unit of material. The seventh column shows the calculated embodied energy for the materials used in the case study house (Btu). Column eight contains additional information about the material, and the last column shows the total embodied energy of each material in MMBtu. Figure 14 contains a graphical presentation of the summary material presented in Table 5 for the case study house, as well as the embodied energy use of the new design to be discussed in the following sections.

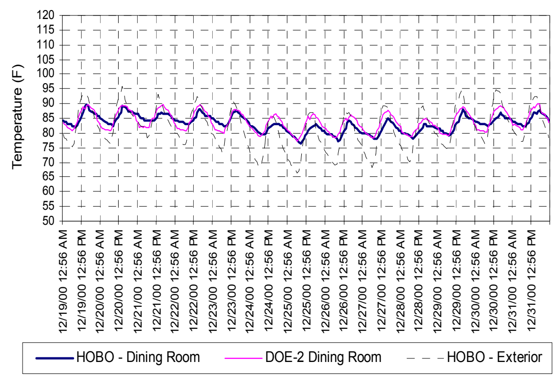

Figure 11. *Dining Room – Zone Temperature Calibration.*

Case Study House vs Proposed New Design

Materials Changes and Embodied Energy Comparisons. Inspection of the materials in Table 5 shows that the masonry walls were the most energy intensive materials used in the house (474.64 MMBtu), followed by the concrete contained in the structural members and floor (296.3 MMBtu), and the structural steel (171.56 MMBtu). The total embodied energy use was calculated to be 1,723 MMBtu, which includes construction fuel energy use (180.9 MMBtu), administrative energy use (132.7 MMBtu), and material energy use (48.2 MMBtu). Although this total embodied energy use was found to be only 77% of the energy use of previously published U.S. residential construction (Table 6), it was clear that significant reductions could still be made with some simple substitution as shown in Tables 7 and 8. The substitutions that substantially reduced the energy use include replacing the masonry walls with lightweight construction, and replacing the aluminum windows with wood-framed windows. Adding double-pane windows increased the insulation, as did the use of insulation in the walls. The total reduction for all the substitutions was 384.8 MMBtu, which reduced the embodied energy use from 1,205.9 MMBtu to 821.23 MMBtu, which represents about ½ of the energy use of the previously published U.S. residence (Figure 14).

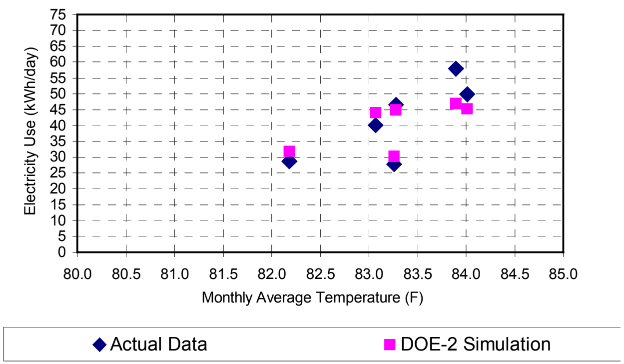

Figure 12. *Calibration – Monthly Electricity Use vs. Temperature.*

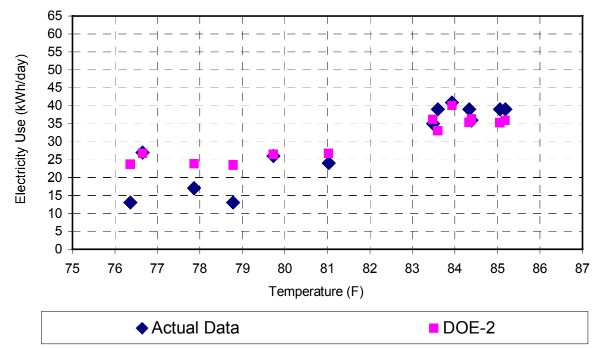

Figure 13.*Calibration – Daily Electricity Use vs. Temperature.*

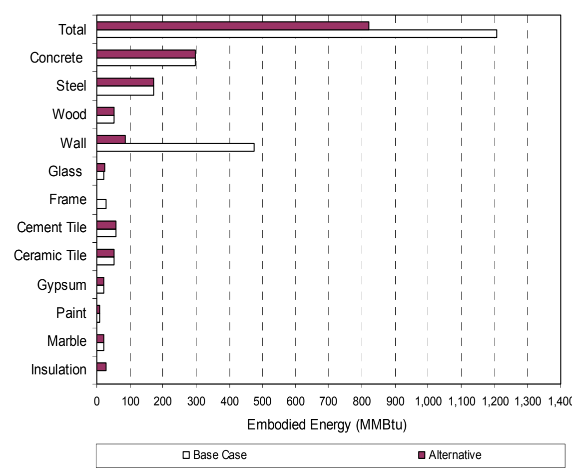

Figure 14. *Case Study House vs. New Design - Embodied Energy Comparisons.*

Concrete	Quantity	Unit	Quantity	IP Unit	Btu / IP Unit	Total Btu	Note	MMBtu
Concrete	87.29	m3	3,083.08	ft3	96,100	296,284,257		296.28
Steel	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
RB 15 mm	256.00	m	780.66	lb	15,700	12,256,378		
RB 12 mm	2,305.70	m	4,499.93	lb	15,700	70,648,827		
RB 9 mm	4,561.80	m	5,007.96	lb	15,700	78,625,048		
RB 6 mm	1,309.48	m	638.91	lb	15,700	10,030,926		
Total	8,432.98	m	10,927.46	lb		171,561,180		171.56
Wood	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Timber 2"*8"	69.00	m	226.39	ft	10,100	2,286,529		
Timber 2"*4"	449.70	m	1,475.47	ft	5,080	7,495,366		
Timber 1.5"*8"	274.40	m	900.31	ft	7,590	6,833,326	interpolate	
Timber 1.5"*4"	920.00	m	3,018.52	ft	3,795	11,455,283	interpolate	
Timber 1.5"*1.5"	1,010.40	m	3,315.12	ft	1,270	4,210,205	1"*2" data	
Timber 1"*8"	93.00	m	305.13	ft	5,080	1,550,076		
Timber 1"*6*	93.00	m	305.13	ft	3,810	1,162,557		
Timber 1"*4"	160.00	m	524.96	ft	2,510	1,317,650		
Timber 1"*1"	104.70	m	343.52	ft	1,270	436,271	1"*2" data	
Wood Panel	19.80	m2	213.05	ft2	16,700	3,557,902	Wood products / Glu-lam	
Parquet	120.75	m2	1,299.27	ft2	9,530	12,382,043	Hardwood Flooring	
Total			146.36	ft3		52,687,207		52.69
Brick	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Brick	336.73	m2	3,623.21	ft2	131,000	474,641,139		474.64
Glass	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Tinted Glass	145.05	m2	1,561.36	ft2	13,700	21,390,581	Single Strength 3/32"	21.39
Aluminum	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Aluminum	72.00	m	155.00	ft2	174,800	27,094,000	1/8" thick, 2 " wide	27.09
Cement	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Cement Tile Roof	317.14	m2	3,413.78	ft2	16,700	57,010,097	Asbestos Shingle	57.01
Ceramic Tile	72.30	m2	778.26	ft2	68,700	53,466,200		53.47
Gypsum	287.50	m2	3,094.73	ft2	6,980	21,601,184	1/2" thick	21.60
Others	**Quantity**	**Unit**	**Quantity**	**IP Unit**	**Btu / IP Unit**	**Total Btu**	**Note**	**MMBtu**
Paint	673.46	m2	7,249.30	ft2	1,390	10,076,527	Exterior (Brick Wall *2)	10.08
Marble	36.75	m2	395.59	ft2	51,000	20,174,919	Quarry Tile	20.17

Table 5. *Case Study House Embodied Energy Calculation.*

Energy in Building Construction Residential 1-family	Stein & Reynolds		Case Study House (3,159 ft2)	
	%	Btu/ft2	Btu/ft2	Btu (Total)
Direct fuel purchases for construction processes	15	105,300	57,264	180,897,000
Administration and professional services	11	77,220	41,994	132,657,800
Transport of materials and equipment	4	28,080	15,270	48,239,200
Manufacture of materials and components	70	491,400	381,760	1,205,980,000
Total	**100**	**702,000**	**545,372**	**1,722,828,571**

Table 6. *Case Study Thai House and American House Embodied Energy Comparison.*

Comparison	Wall	Quantity	Unit	Btu / Unit	Total Btu	MMBtu
Original House	Brick	3,623.21	ft2	131,000	474,641,139	474.64
	Lightweight-Exterior	2,713.99	ft2	25,394	68,919,184	68.92
Alternative House	Lightweight-Interior	909.22	ft2	19,080	17,347,918	17.35
Comparison	**Glass**	**Quantity**	**Unit**	**Btu / Unit**	**Total Btu**	**MMBtu**
Original House	Single-Pane	1,561.36	ft2	13,700	21,390,581	21.39
Alternative House	Double-Pane	1,561.36	ft2	15,400	24,044,887	24.04
Comparison	**Window Frame**	**Quantity**	**Unit**	**Btu / Unit**	**Total Btu**	**MMBtu**
Original House	Aluminum	155.00	ft2	174,800	27,094,000	27.09
Alternative House	Wood Frame	236.23	ft	2,510	592,942	0.59
Comparison	**Insulation**	**Quantity**	**Unit**	**Btu / Unit**	**Total Btu**	**MMBtu**
Original House	No Insulation	-	-	-	-	-
	Roof Insulation	1,299.78	ft2	6,860	8,916,523	8.92
Alternative House	Wall Insulation	2,715.07	ft2	6,860	18,625,380	18.63

Table 7. *Base Case vs. New Design - Materials Changed and Embodied Energy Comparisons.*

Materials	Embodied Energy (MMBtu)	
	Base Case	New Design
Concrete	296.28	296.21
Steel	171.56	171.56
Wood	52.69	52.69
Wall	**474.64**	**86.27**
Glass	**21.39**	**24.04**
Frame	**27.09**	**0.59**
Cement Tile	57.01	57.01
Ceramic Tile	53.47	53.47
Gypsum	21.60	21.60
Paint	10.08	10.08
Marble	20.17	20.17
Insulation	**0.00**	**27.54**
Total	**1,205.98**	**821.23**

Table 8. *Case Study House vs. New Design - Embodied Energy Comparisons. The bold items are the items that were changed from the base case to a new design.*

Reductions in Operational Energy Use. The next step in the energy use reduction was to select new energy conserving features that could be added to the new design that would reduce the annual energy use. A number of different features were investigated, and the following features were found to be the most beneficial: lightweight wall with R-11 batt insulation, cement-tile roof with R-11 roof insulation, double-pane tinted glass with reflective coating, white walls and roof, use of landscape to reduce reflected radiation, and programmable thermostats. To evaluate the impact of each of these features, the DOE-2 simulation was first calibrated to the base-case house, then a separate input file was created to represent each individual measure. Finally, a combined file was created with the most effective measures that represented the new house.

The insulated roof and walls yielded a modest decrease in the energy use. The light-weight R-11 walls reduced the annual energy use by almost 4% compared to the un-insulated walls, and adding R-11 insulation to the roof reduced the annual energy use by 2.6%. These small reductions were felt to be due to the limited air conditioning of the bedrooms, and an absence of heating . The double-pane, tinted glazing reduced annual energy use by 12.5%, which are mostly cooling load reductions.

Changing the exterior surfaces to more reflective colors reduced energy use by about 4%, which is smaller than expected. Most likely due to the lower-than-expected temperatures observed in the ventilated roof (Figure 6). The choice of green vegetation has a modest decrease of slightly more than 1%. This too is smaller than expected because the DOE-2 program only reduces the reflected gain component of the direct solar radiation, and does not include any changes to the lower, surrounding ambient temperatures caused by shaded surfaces that surround the building. In summary, the combined new construction features significantly reduced the annual energy use (Figure 15). Over the 50 year estimated life of the building, as shown in Table 9, the expected energy use was reduced from 2,748 MMBtu to 1,948 MMBtu, a 30% reduction.

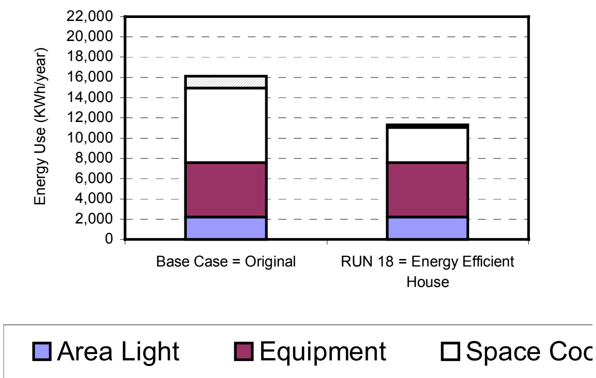

Figure 15. *Base Case vs. Energy Efficient House.*

Energy Consumption (MMBtu)	Base Case	New Design
Energy Used in Building Construction	1,205.98	821.23
Energy Used in Building Operation	2,748.00	1,932.00
Energy Used in Building Demolition	20.03	20.03
Lifetime Building Energy Consumption	3,974.01	2,773.26

Table 9. *Base Case vs. New Design – Lifetime Building Energy Consumption Comparisons.*

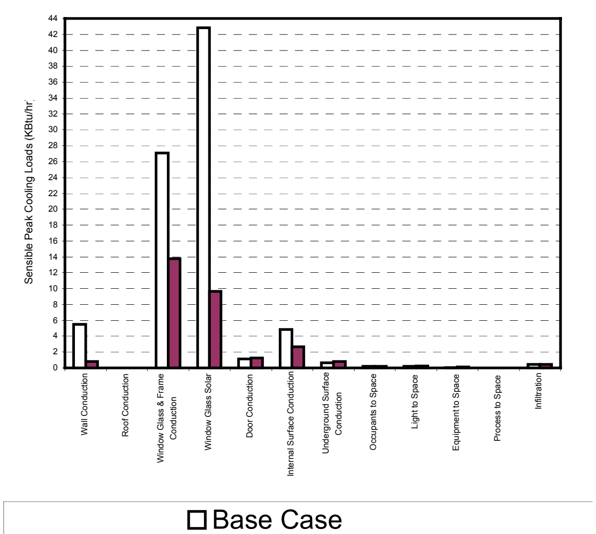

Figure 16*. Base Case vs. New Design – Building Peak Load Component Comparison.*

Figure 16 has been provided to provide further insight into where the savings are coming from. In this figure the peak cooling loads are shown, which indicate that the largest reductions are attributable to the reduced solar gains, reduced heat conduction through the windows, and reduced heat gains through the wall and roof.

Energy Used in Building Demolition. From the research of Lund University, Sweden, energy used in building demolition is composed of 2 major parts: 1) energy used in building demolition and 2) energy used to remove deconstructed materials. Each task consumes about 3,171 Btu/ft^2 (10 kWh/m^2). Since the gross area of the case study house is 3,159 ft^2 (293.5 m^2), the calculated demolition energy was estimated to be 20.03 MMBtu for both the case-study house and the energy efficient house (Table 9 and Figure 17). No credit was applied for the recycling of materials during the demolition process.

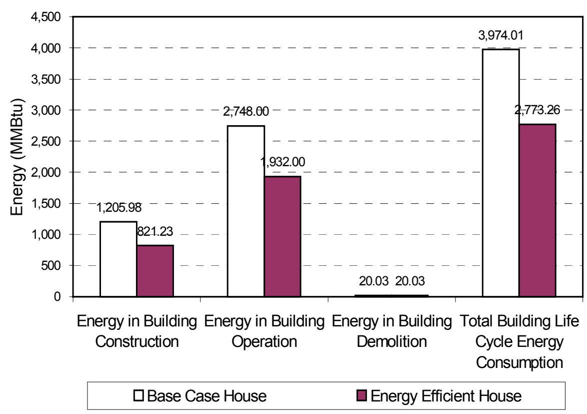

Figure 17. *Base Case vs. New Design – Lifetime Building Energy Consumption Comparisons.*

Lifetime energy use. Finally, for the lifetime building energy consumption, three major parts: 1) the energy used in building construction, 2) the energy used in building operation, and 3) the energy used in building demolition were combined. Table 9 and Figure 16 show the case study house's lifetime energy consumption. The results show that the new design reduced construction energy use from 1,286 to 821 MMBtu (a 36% reduction), the energy used to operate the building was reduced from 2,748 to 1,932 MMBtu (a 30% reduction), demolition energy use remained unchanged. The total lifetime energy use was reduced from 3,974 to 2,773 MMBtu (a 30% reduction).

SUMMARY

This study has examined the lifetime building energy consumption of a typical house in Bangkok, Thailand. The lifetime building energy consumption is composed of three major components: 1) the energy used in building construction (embodied energy), 2) the energy used in building operation (annual energy), and 3) the energy used in building demolition (demolition energy).

The study used measured environmental and energy use data from a case-study house in Thailand. The embodied energy use was calculated from the as-built drawings, annual energy use was calculated using a calibrated DOE-2 simulation. An energy efficient design was chosen that reduced embodied energy use and annual energy use. The results from the analysis showed that the total lifetime energy use was reduced from 3,974 to 2,773 MMBtu (a 30% reduction). This was accomplished by carefully replacing the most energy intensive materials with less energy intensive materials that were also energy efficient, namely the masonry walls, insulation in the ceiling and energy efficient windows.

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